

Observation of the $D_1(2420) \rightarrow D\pi^+\pi^-$ decays.

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We report on the first observation of $D_1(2420) \rightarrow D\pi^+\pi^-$ decays (where the contribution from the dominant known $D_1 \rightarrow D^*\pi$ decay mode is excluded) in the $B \rightarrow D_1\pi$ decays. The observation is based on $15.2 \times 10^7 B\bar{B}$ events collected with the Belle detector at the KEKB collider. We also set 90% confidence level upper limits for the $D_2^* \rightarrow D^{(*)}\pi^+\pi^-$ and $D_1 \rightarrow D^*\pi^+\pi^-$ decays in the $B \rightarrow D_2^*(2460)\pi$ and $B \rightarrow D_1(2420)\pi$ decays, respectively.

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The $D_1 \rightarrow D^*\pi$ decay is currently known to be the primary decay mode of the $D_1(2420)$ meson [1]. However, the transitions $D_1 \rightarrow D\pi\pi$ via other intermediate quasi-two-body resonance states or via non-resonant decays are possible and may contribute to the D_1 total width. Measurements of their branching ratios and analysis of the decay dynamics are particularly relevant to a study of production rates of various D^{**} excitations in B decays.

The ratio of the branching fractions $R = \mathcal{B}(B^- \rightarrow D_2^{*0}\pi^-)/\mathcal{B}(B^- \rightarrow D_1^0\pi^-)$ is calculated in HQET and the factorization approximation in Refs. [2, 3]. In Ref. [2], R is found to depend on the values of the subleading Isgur-Wise functions ($\hat{\tau}_{1,2}$) describing Λ_{QCD}/m_c corrections; thus measurement of R can be used to estimate the subleading functions. In Ref. [3], some of the subleading terms are estimated and the ratio is determined to be $R \approx 0.35 \left| (1 + \delta_8^{D_2}) / (1 + \delta_8^{D_1}) \right|^2$, where $\delta_8^{D_1(D_2)}$ are non-factorizable corrections that are expected to be small.

The first observation of D^{**} (denotes P -wave D excitations) production in B decays was reported by CLEO [4]. From their studies and the measurement of the ratio $\mathcal{B}(D_2^{*0} \rightarrow D^+\pi^-)/\mathcal{B}(D_2^{*0} \rightarrow D^{*+}\pi^-)$ [5, 6] the R value was determined to be $R = 1.8 \pm 0.8$, where it was assumed that decays of D_1 and D_2^* mesons are saturated by the two-body $D\pi$, $D^*\pi$ modes. Recently the branching fractions for the decays $B \rightarrow D^{**}\pi \rightarrow D^{(*)}\pi\pi$ have been measured with better accuracy [7], resulting in $R = 0.77 \pm 0.15$. The existence of $D_{(1,2)}$ decay channels other than $D_1 \rightarrow D^{(*)}\pi$ can also affect the R value, either decreasing or increasing the currently observed 2.8σ difference between the prediction and experimental results.

In this Letter we report the first observation of the $D_1^+ \rightarrow D^+\pi^-\pi^+$ and $D_1^0 \rightarrow D^0\pi^-\pi^+$ decays. The D_1 mesons were reconstructed from the $\bar{B}^0 \rightarrow D_1^+\pi^-$ and $B^- \rightarrow D_1^0\pi^-$ decays, respectively. The results are based

on a sample of $15.2 \times 10^7 B\bar{B}$ pairs produced at the KEKB asymmetric energy e^+e^- collider [8]. The inclusion of charge conjugate states is implicit throughout this report.

The Belle detector has been described elsewhere [9]. Charged tracks are selected with a set of requirements based on the average number of hits in the central drift chamber (CDC) and on the distance of the closest approach to the interaction point. Track momentum transverse to the beam axis of at least 0.05 GeV/ c is required for all tracks in order to reduce the combinatorial background. For charged particle identification (PID), the combined information from specific ionization in the CDC (dE/dx), time-of-flight scintillation counters and aerogel Čerenkov counters is used. Charged kaons are selected with PID criteria that have an efficiency of 88%, a pion misidentification probability of 8%, and negligible contamination from protons. All charged tracks with PID responses consistent with a pion hypothesis that are not positively identified as electrons are considered as pion candidates. Photon candidates are selected from calorimeter showers not associated with charged tracks. An energy deposition of at least 30 MeV and a photon-like shape are required for each candidate. Pairs of photons with an invariant mass within 12 MeV/ c^2 ($\sim 2.5\sigma$) of the π^0 nominal mass [1] are considered as π^0 candidates.

We reconstruct $D^0(D^+)$ mesons in the $K^-\pi^+$ ($K^-\pi^+\pi^+$) decay channel and require the invariant mass to be within 15 MeV/ c^2 ($\sim 3\sigma$) of the $D^0(D^+)$ mass. Then, $D^{*0}(D^{*+})$ mesons are reconstructed in the $D^0\pi^0(D^0\pi^+)$ decay mode. The calculated mass difference between $D^{*0}(D^{*+})$ and D^0 candidates is required to be within 2 (1.5) MeV/ c^2 ($\sim 2.5\sigma$) of the expected value [1]. For $D^* \rightarrow D^0\pi$ decays the $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ mode is also included (the same D^* parameters were used as above).

TABLE I: Number of events, efficiencies and branching fraction products of $B \rightarrow D^{**}\pi, D^{**} \rightarrow D^{(*)}\pi^+\pi^-$ decays.

Mode	N_{sig}	ε (10^{-2})	\mathcal{B} (10^{-4})	Significance
$B^- \rightarrow D_1^0\pi^-, D_1^0 \rightarrow D^0\pi^-\pi^+$	151 ± 24	14.1	$(1.85 \pm 0.29 \pm 0.35_{-0.46}^{+0.0})$	8.7σ
$\bar{B}^0 \rightarrow D_1^+\pi^-, D_1^+ \rightarrow D^+\pi^-\pi^+$	124 ± 20	9.9	$(0.89 \pm 0.15 \pm 0.17_{-0.26}^{+0.0})$	10σ
$B^- \rightarrow D_1^0\pi^-, D_1^0 \rightarrow D^{*0}\pi^+\pi^-$	< 1.2	2.2	< 0.06	-
$\bar{B}^0 \rightarrow D_1^+\pi^-, D_1^+ \rightarrow D^{*+}\pi^+\pi^-$	< 12.0	3.4	< 0.33	-
$B^- \rightarrow D_2^{*0}\pi^-, D_2^{*0} \rightarrow D^{*0}\pi^+\pi^-$	< 4.4	2.2	< 0.22	-
$\bar{B}^0 \rightarrow D_2^{*+}\pi^-, D_2^{*+} \rightarrow D^{*+}\pi^+\pi^-$	< 9.0	3.4	< 0.24	-

We combine $D^{(*)}$ candidates with $\pi^-\pi^-\pi^+$ to form B mesons. Candidate events are identified by their center-of-mass (CM) energy difference, $\Delta E = (\sum_i E_i) - E_{beam}$, and the beam constrained mass, $M_{bc} = \sqrt{E_{beam}^2 - (\sum_i \vec{p}_i)^2}$, where E_{beam} is the beam energy and \vec{p}_i and E_i are the momenta and energies of the decay products of the B meson in the CM frame. We define the signal region as $5.273 \text{ GeV}/c^2 < M_{bc} < 5.285 \text{ GeV}/c^2$ and $|\Delta E| < 25 \text{ MeV}$. The sidebands are defined as $5.273 \text{ GeV}/c^2 < M_{bc} < 5.285 \text{ GeV}/c^2$ and $25 \text{ MeV} < |\Delta E| < 50 \text{ MeV}$. If there is more than one B candidate in an event, the one with $D^{(*)}$ mass closest to the nominal value and the best $\pi^-\pi^-\pi^+$ vertex is chosen. We use Monte Carlo (MC) simulation to model the detector response and determine the acceptance [10].

Variables that characterize the event topology calculated in the CM frame are used to suppress background from the two-jet-like $e^+e^- \rightarrow q\bar{q}$ continuum process. We require $|\cos\theta_{thr}| < 0.80$, where θ_{thr} is the angle between the thrust axis of the B candidate and that of the rest of the event; this eliminates 77% of the continuum background while retaining 78% of the signal events. We also define a Fisher discriminant, \mathcal{F} , which is based on the production angle of the B candidate, the angle of the thrust axis with respect to the beam axis, and nine parameters that characterize the momentum flow in the event [11]. We impose a requirement on \mathcal{F} that rejects 67% of the remaining continuum background and retains 83% of the signal.

To suppress the large contribution from the dominant $D_1 \rightarrow D^*\pi \rightarrow D\pi\pi$ decay mode we apply a requirement on the invariant mass of the relevant $D\pi$ combination $|(m_{D\pi} - m_D) - (m_{D^{*0}}^{PDG} - m_D^{PDG})| > 6 \text{ MeV}/c^2$ [1] (10σ).

The ΔE and $M_{D^{(*)}\pi\pi}$ distributions for the selected $B \rightarrow D_1\pi, D_1 \rightarrow D^{(*)}\pi\pi$ candidates are shown in Fig. 1. To plot the ΔE distributions, we require M_{bc} to lie in the signal region with an additional requirement $|M_{D^{(*)}\pi\pi} - M_{D_1}| < 25 \text{ MeV}/c^2$, where M_{D_1} is the D_1 world average mass value; for the $M_{D^{(*)}\pi\pi}$ distributions we select events from the ΔE signal region. (Although there are two $D\pi^+\pi^-$ combinations, they are kinematically separated in the D_1 mass region.) Clear signals are observed for $B^- \rightarrow D_1^0\pi^-, D_1^0 \rightarrow D^0\pi^-\pi^+$ and $\bar{B}^0 \rightarrow D_1^+\pi^-, D_1^+ \rightarrow D^+\pi^-\pi^+$ decays. For branch-

ing fraction calculations we use signal yields determined from the fit to $M_{D\pi\pi}$ distributions as it allows us to directly estimate a possible contribution from $B \rightarrow D_2\pi, D_2 \rightarrow D\pi\pi$ decay. The signal shape distribution is parameterized by a convolution of a resolution Gaussian ($\sigma = 2.5 \text{ MeV}/c^2$) with a signal Breit-Wigner function; the background is represented by a linear function. The D_1 mass and width determined from the fit are $M_{D_1^0} = 2426 \pm 3 \pm 1 \text{ MeV}/c^2$ (statistical and systematic error, respectively), $\Gamma_{D_1^0} = 24 \pm 7 \pm 8 \text{ MeV}/c^2$ for D_1^0 and $M_{D_1^+} = 2421 \pm 2 \pm 1 \text{ MeV}/c^2$, $\Gamma_{D_1^+} = 21 \pm 5 \pm 8 \text{ MeV}/c^2$ for D_1^+ ; these are consistent with the world average values [1]. The signal yields are given in Table I (in the cited branching ratios the first and second errors are statistical and systematic; where a third error given is due to model uncertainty). For the $B \rightarrow D_1\pi \rightarrow D^*\pi^-\pi^+\pi^+$ decay channels, we do not observe statistically significant signals and thus determine 90% CL upper limits [12] for their branching fractions. In the fit to the $M_{D^*\pi\pi}$ distribution, we fix the D_1 mass and width at their world average values. The statistical significance of signals quoted in Table I is defined as $\sqrt{-2 \ln(L_0/L_{max})}$, where L_{max} and L_0 denote the maximum likelihood with the nominal signal yield and with the signal yield fixed at zero, respectively.

To account for contamination from other possible D_1 production mechanisms (such as $e^+e^- \rightarrow c\bar{c}$ continuum production or semileptonic $B \rightarrow D_1 l \bar{\nu}$ decays), we fit the $M_{D\pi\pi}$ distribution for events in the ΔE sidebands. In this fit, we fix the D_1 mass and width at their world average values. The fits give -6 ± 8 events for the D_1^0 and 10 ± 11 events for the D_1^+ .

The $B \rightarrow D_2^*(2460)\pi, D_2^* \rightarrow D\pi^+\pi^-$ decay may also contribute to the $B \rightarrow D\pi^-\pi^-\pi^+$ final state. To analyse a possible effect, we made a simultaneous fit of the $M(D_1^0\pi^+\pi^-)$ and $M(D_1^+\pi^+\pi^-)$ distributions, where we assume isospin invariance and require the ratio $N(D_2^*)/N(D_1)$ to be the same for both charge combinations. The fit finds the ratio $N(D_2^*)/N(D_1) = 0.33 \pm 0.14$ and signal yields of $N(D_1^0) = 120 \pm 17$, $N(D_1^+) = 107 \pm 16$. Thus, we set a 90% CL upper limit for D_2^* : $\mathcal{B}(B \rightarrow D_2^*\pi^-) \times \mathcal{B}(D_2^* \rightarrow D\pi^+\pi^-) < 0.55\mathcal{B}(B \rightarrow D_1\pi^-) \times \mathcal{B}(D_1 \rightarrow D\pi^+\pi^-)$ [13]. The number of events

for the D_1 mechanism obtained in the fit with the $\frac{D_2^*}{D_1}$ ratio fixed to 0.46 gives the model uncertainty for the D_1 yield: $^{+0}_{-21}\%$. Another asymmetric uncertainty, coming from the other possible D_1 sources, is $^{+0}_{-10}\%$ for D_1^0 and $^{+0}_{-22}\%$ for D_1^\pm . These two uncertainties are combined in the final results as "model" uncertainty.

The signal yields extracted from the ΔE distributions are used only for a consistency check of the results. The ΔE signal shape is parameterized by a Gaussian with parameters determined from signal MC. The ΔE background shape is described by a linear function. We restrict the fit to the range $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$ to avoid contributions from other B decays, where an additional pion is not reconstructed. Signal yields obtained from the fits to ΔE distributions are 106 ± 12 for $D^0 \pi^+ \pi^-$ and 96 ± 13 for $D^+ \pi^+ \pi^-$, while the corresponding reconstruction efficiencies are 10.8% and 7.6%, respectively. Thus the obtained reconstructed event numbers by the two methods are consistent within the statistical uncertainty.

In order to determine the total $D_1 \rightarrow D\pi\pi$ width, analysis of final states with neutral pions is required. With only the $D_1 \rightarrow D\pi^+ \pi^-$ branching fraction measurement, the analysis of the decay dynamics could also be useful to determine the total $D_1 \rightarrow D\pi\pi$ width. As the limited statistics do not allow us to perform the full amplitude analysis, we consider the one-dimensional projections of several variables: $M_{D\pi}$, $M_{\pi^+ \pi^-}$, $\cos \Theta(\pi_B^- \pi_{D^{**}}^-)$, $\cos \Theta(\pi_B^- \pi_{D^{**}}^+)$, and $\cos \Theta(\pi_B^- D)$ (where all angles are calculated in the D^{**} rest frame). Although these variables are not independent, they highlight each model's features. For instance, the helicity angle distributions differentiate between the $D_1 \rightarrow D(\pi\pi)$ and $D_1 \rightarrow (D\pi)\pi$ models. We select events from the B signal region with the additional requirement $|M(D\pi\pi) - M_{D_1}| < 25 \text{ MeV}/c^2$. Decays through the following quasi-two-body intermediate states are considered: $D_1 \rightarrow D\rho^0 \rightarrow D\pi^+ \pi^-$, $D_1 \rightarrow D_0^*(2308)\pi \rightarrow D\pi\pi$ and $D_1 \rightarrow Df_0(600) \rightarrow D\pi^+ \pi^-$ (we set $M_{f_0} = 0.8 \text{ GeV}/c^2$ and $\Gamma_{f_0} = 0.8 \text{ GeV}/c^2$; the $D_0^*(2308)$ parameters are taken from Ref. [7]). We use the simplest non-trivial Lorentz-invariant expressions for the corresponding matrix elements in MC simulation [14]. We fit the experimental data with different models. For each variable we plot two distributions: one from the signal region and the other from the ΔE sideband. We perform a simultaneous fit to these distributions, assuming a Poisson-like profile in each bin whose mean is the sum of the background and signal (for a given model) in the signal region or the background only in the sideband. The obtained differences of likelihood values for all variables are listed in Table II. Figure 2 shows the $M_{\pi^+ \pi^-}$ and $\cos \Theta(\pi_B^- D)$ distributions along with expectations based on different $D_1 \rightarrow D\pi^+ \pi^-$ decay models [15]. Although the $D_1 \rightarrow D_0^* \pi$ decay mechanism describes the data best, some contribution from

TABLE II: Comparison of goodness-of-fit tests for the considered $D_1 \rightarrow D\pi\pi$ decay models.

Distribution	$(-2 \ln L_{D\rho}/L_{D_0^* \pi})^{1/2}$	$(-2 \ln L_{Df_0}/L_{D_0^* \pi})^{1/2}$
	D^0, D^+	D^0, D^+
$M_{D\pi}$	2.5, 2.7	1.9, 2.9
$M_{\pi^+ \pi^-}$	3.4, 1.6	5.2, 4.7
$\cos \Theta(\pi_B^- \pi_{D^{**}}^+)$	1.6, 2.5	-2.0 ^a , 3.4
$\cos \Theta(\pi_B^- \pi_{D^{**}}^-)$	2.5, 3.0	4.0, 2.9
$\cos \Theta(\pi_B^- D)$	2.0, 0.5	3.2, 4.0

^aIn this case $L_{Df_0} < L_{D_0^* \pi}$

other mechanisms cannot be excluded completely.

It is interesting to examine the dependence of the R value on the decay mechanism. The expression for R can be written as $s_1 \times \mathcal{B}(B^- \rightarrow D_2^{*0} \pi^-, D_2^{*0} \rightarrow D^{*+} \pi^-) / (s_1 \times \mathcal{B}(B^- \rightarrow D_1^0 \pi^-, D_1^0 \rightarrow D^{*+} \pi^-) + s_2 \times \mathcal{B}(B^- \rightarrow D_1^0 \pi^-, D_1^0 \rightarrow D^0 \pi^+ \pi^-))$ where s_i is a scale factor that recovers the full width from the single decay channel. (It includes branching fractions of other possible decays of both D^{**} and a meson from its decay products.) Following the procedure used in Ref. [7] and fixing s_1 at 3/2, we can calculate s_2 factors for different models: $s_2(D^{*0} \rightarrow D_0^{*+} \pi^-) = 9/4$ (disregarding possible interference effects in $D_1^0 \rightarrow D^+ \pi^- \pi^0$ decays), $s_2(D^{*0} \rightarrow D^0 \rho) = 3$, $s_2(D^{*0} \rightarrow D^0 f_0) = 3/2$. Using the branching fractions measured in Ref. [7] and here, the central value for R depends on the decay model: 0.50 for $D\rho$, 0.60 for Df_0 and 0.54 for $D_0^* \pi$.

The following sources of systematic errors are considered: tracking efficiency (8% overall, integrated over particle momenta), kaon identification efficiency (2% overall), π^0 reconstruction efficiency (8%), D branching fraction uncertainties (2%-7%), MC statistics (2%), model uncertainty in MC efficiency (10%), uncertainty caused by variation of cuts (5%), background shape uncertainty (10%). The uncertainty in the tracking efficiency is estimated using partially reconstructed $D^{*+} \rightarrow D^0 [K_S^0 \pi^+ \pi^-] \pi^+$ decays. The kaon identification uncertainty is determined from $D^{*+} \rightarrow D^0 [K^- \pi^+] \pi^+$ decays. The π^0 reconstruction uncertainty is obtained using D^0 decays to $K^- \pi^+$ and $K^- \pi^+ \pi^0$. To determine the systematic uncertainty in the signal yield extraction, we use different parameterizations for the background events. The overall systematic uncertainty is 19% for $B \rightarrow D\pi\pi\pi$ and 21% for $B \rightarrow D^* \pi\pi\pi$. We assume equal production rates for $B^+ B^-$ and $B^0 \bar{B}^0$ pairs and do not include the corresponding uncertainty in the total systematic error.

The $B^- \rightarrow D^0 \pi^+ \pi^- \pi^-$ final state also includes the $D^{*+} \pi^- \pi^-$ intermediate state with $D^{*+} \rightarrow D^0 \pi^+$. We reverse the D^* veto requirement to select $D^{*+} \pi^+ \pi^-$ events and measure the branching ratio $\mathcal{B}(B^- \rightarrow D^{*+} \pi^- \pi^-) = (1.27 \pm 0.07) \times 10^{-4}$ (based on a sample of $85 \times 10^6 B \bar{B}$

events), that agrees well with the value of $\mathcal{B}(B^- \rightarrow D^{*+}\pi^-\pi^-) = (1.25 \pm 0.07) \times 10^{-4}$ measured earlier [7].

In summary, we report the first observation of $D_1(2420) \rightarrow D\pi^+\pi^-$ decays (with the dominant $D_1 \rightarrow D^*\pi$ contribution excluded). The measured branching ratios with the corresponding statistical significances and systematic uncertainties are presented in Table I. We find the upper limit for the possible D_2^* contribution to these results: $\mathcal{B}(B^- \rightarrow D_2^*\pi^-) \times \mathcal{B}(D_2^* \rightarrow D\pi^+\pi^-) < 0.55\mathcal{B}(B^- \rightarrow D_1\pi^-) \times \mathcal{B}(D_1 \rightarrow D\pi^+\pi^-)$. No statistically significant signal has been observed for the $D^{**} \rightarrow D^*\pi^+\pi^-$ decays. The corresponding 90% CL upper limits are listed in Table I. Analysis of the $D_1 \rightarrow D\pi^+\pi^-$ dynamics shows that the decay model $D_1 \rightarrow D_0^*\pi$ gives the best description of the data. The $R = \mathcal{B}(B^- \rightarrow D_2^*\pi^-)/\mathcal{B}(B^- \rightarrow D_1^0\pi^-)$ value calculated assuming $D_1 \rightarrow D_0^*\pi$ dominates is 0.54 ± 0.18 ; this is $\sim 2\sigma$ lower than the previously published one.

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- [13] As most of the systematic uncertainties cancel in the ratio of the branching fractions, the systematic uncertainty is

negligible.

[14] We use the following expressions for matrix elements for

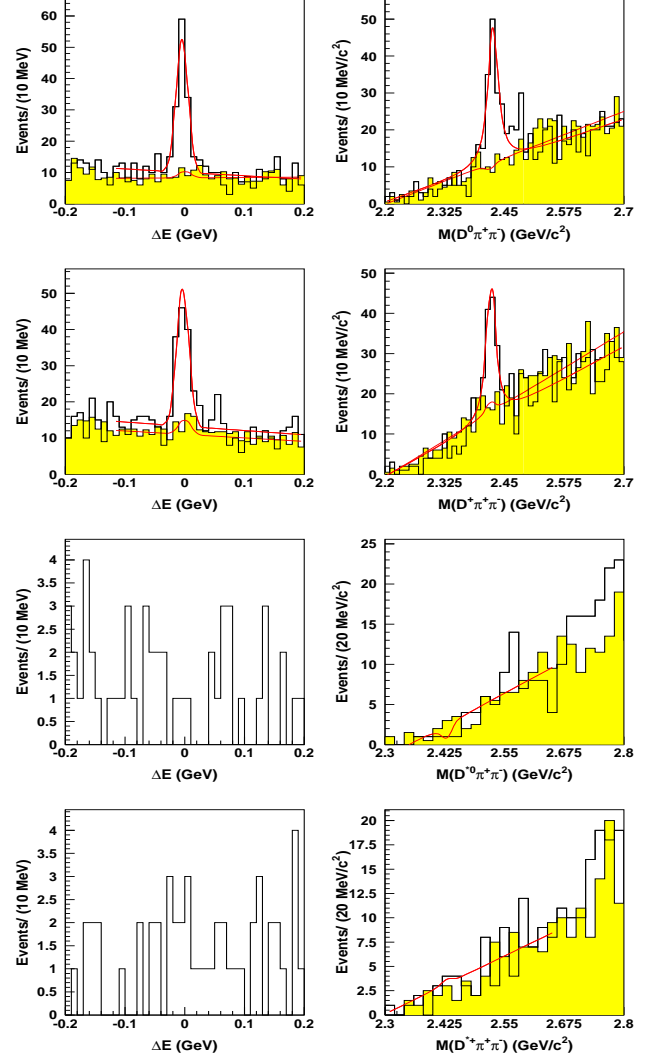


FIG. 1: ΔE (left) and $M_{D\pi\pi}$ (right) distributions for the $D_1^0 \rightarrow D^0\pi^-\pi^+$ (first row), $D_1^+ \rightarrow D^+\pi^-\pi^+$ (second row), $D_1^0 \rightarrow D^{*0}\pi^-\pi^+$ (third row) $D_1^+ \rightarrow D^{*+}\pi^-\pi^+$ (fourth row). Open histograms represent the data from the signal area, hatched histograms show the $M_{D\pi\pi}$ (where applicable) and ΔE sidebands, respectively, the curves are the fit results - for the signal area and sidebands.

the $D_1 \rightarrow D\pi\pi$ decay: $F^{\nu\eta}(B^0, \pi_B^+)F_{\mu\nu}(\bar{D}_0^*, \pi_{D_1^-}^-) \cdot P(D_1^-)_\eta P(D_1^-)^\mu$, $F^{\phi\eta}(B^0, \pi_B^+)F_{\mu\phi}(f^0, D_1^-) \cdot P(D_1^-)_\eta P(D_1^-)^\mu$, $F^{\nu\eta}(B^0, \pi_B^+)F_{\nu\mu}(\rho^0, \pi_\rho^+ - \pi_\rho^-) \cdot P(D_1^-)_\eta P(D_1^-)^\mu$, where the following notation is used: $F^{\mu\nu}(A, B) = P_A^\mu P_B^\nu - P_A^\nu P_B^\mu$, $P(B - C) = P(B) - P(C)$ and P stands for a 4-momentum.

[15] In case of the Df_0 model the key $\cos \Theta(\pi_B^- D)$ distribution is practically independent of the f_0 mass and width.

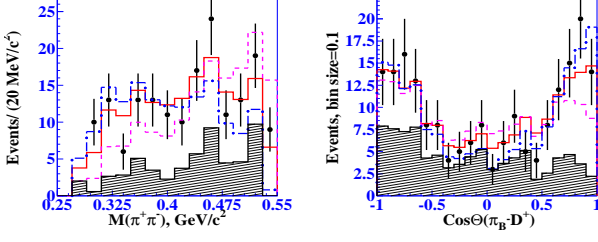


FIG. 2: $M_{\pi^+\pi^-}$ (left) and $\cos\Theta(\pi_B^- D)$ (right) distributions for the $D_1^0 \rightarrow D^0 \pi^- \pi^+$ and $D_1^+ \rightarrow D^+ \pi^- \pi^+$, respectively. Points with error bars represent the experimental data, solid line - $D^{*0}\pi$, dashed - $D\rho$, chain - Df_0 models with the expected background added. The hatched histogram corresponds to expected background (from ΔE sidebands).